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Spinal exercise prescription in sport

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Spinal exercise prescription in sport: classifying physical training and rehabilitation by intention and outcome

Context: Identification of strategies to prevent spinal injury, optimise rehabilitation, and enhance performance is a priority for practitioners. Different exercises produce different effects on neuromuscular performance. Clarity of the purpose of a prescribed exercise is central to successful outcome. There is a need to classify spinal exercises according to the objective of the exercise and planned physical outcome.

Objective: The objectives of this study were to define the modifiable spinal abilities which underpin optimal function during skilled athletic performance, and to classify spinal exercises according to the objective of the exercise and intended physical outcomes.

Design: A qualitative consensus method of 4 iterative phases. 1] Exploratory panel carried out an extended review the literature to identify key themes and sub themes to inform the definition of physical abilities, exercise categories and physical outcomes. 2] Expert project group reviewed panel findings. 3] Draft classification discussed with physiotherapists (n=49), and international experts. 4] Revised classification reviewed by lead physiotherapy and strength & conditioning teams (n=17). Consensus was defined as unanimous agreement.

Results: Spinal abilities were defined in four categories: mobility, motor control, work capacity, and strength. Exercises were sub-classified by functionality as non-functional or functional; and by spinal displacement as either static (neutral spinal posture with no segmental displacement) or dynamic (dynamic segmental movement). The proposed terminology and classification supports commonality of language for practitioners.

Conclusions: The Spinal Exercise Classification will support clinical reasoning through description of a framework of spinal exercise objectives which clearly define the nature of exercise prescription required to deliver intended physical outcomes.

Key Words: spine, back, exercise prescription, classification, training, rehabilitation

Key Points

- The spinal abilities underpinning optimal function during skilled athletic performance have been evaluated and a comprehensive framework of exercise and physical outcomes has been established.
- The framework provides a basis for clinical reasoning in spinal exercise prescription and establishes a platform for shared understanding to enable interdisciplinary working, applicable within a diverse spectrum of musculoskeletal practice.

INTRODUCTION

Injury epidemiological data suggests that the prevalence of back pain in athletes is between 30-50%[1,2]. Injury surveillance data collected by The English Institute of Sport (EIS) between 2009-2012 across 11 Olympic sports indicated that thoracic and lumbar spine injury (LSI) accounted for 14.2% of all injuries and resulted in 737 days lost from training and competition (unpublished data). Injury was prevalent in sports which place significant demands on the spine through intensive and/or repetitive directional loading[3,4] including gymnastics, diving, weightlifting, cricket and rowing. Identification of strategies to prevent spinal injury, optimise spinal rehabilitation, and enhance spinal performance is a priority for practitioners.

Spinal function has been defined as the ability to create, absorb and transfer force and motion to the terminal appendicular segment during performance of skilled motor tasks[5]. Theoretical definitions of 'core stability' (CS) however, fail to represent the relationship between passive anatomical structure and the complex neuromuscular system coordination required to maintain spinal integrity under varying loads and motion demands. The nature of spinal integrity during sporting activity is therefore task specific. The theoretical basis of 'optimal' movement efficiency is therefore an expression of the co-ordinated interaction of numerous physical abilities underpinning spinal function[6].

Specificity of training enables the development of targeted outcome measures to enhance performance. During rehabilitation, practitioners must also consider the impact of pathology/pain on specific physical abilities and identify effective strategies to address dysfunction. The use of exercise is unequivocally accepted as part of a multifaceted approach to training and rehabilitation[7]. Identification of sub optimal physical performance forms the basis of clinical reasoning to inform exercise prescription.

Historically, the nature of spinal exercise prescription has been subject to widespread debate[8,9], centred on the relative understanding and importance of CS; driven by its role in the management of chronic low back pain[10]. Whilst significant progress in detailing the components of spinal stability alongside its relationship with spinal mobility has been made[11], uni-dimensional paradigms of exercise prescription persist. For example, approaches have attempted to isolate groups of core muscles and/or their function, despite the importance of a synergistic contribution of many different muscles in order to balance stability and movement demands[12]. Furthermore, given that different exercises produce different effects on neuromuscular performance, use of the term CS is problematic as it does not adequately define the intent of an exercise, and is often used by practitioners when attempting to deliver several different training or rehabilitation outcomes. As a consequence, spinal exercises (and often exercises in general) are frequently described by name, equipment used, or place performed (e.g. Pilates/core exercises, mat exercises, gym exercises), rather than by intent, loading and execution. Failure to delineate exercise intention may also lead to miscommunication between practitioners. The objectives of this study were twofold:

1. To define the modifiable spinal abilities which underpin optimal function during skilled athletic performance and clarify the impact of spinal pain/pathology.

2. To classify spinal exercises according to the objective of the exercise and intended physical outcomes to inform training and rehabilitation.

METHODS

Qualitative consensus method of 4 iterative phases (Figure 1). A conceptual framework was defined to underpin the study methods (Figure 2). The framework forms an analytical tool that was used in phase 1 to organise the ideas emerging from the literature. It provided a structure of starting principles and assumptions that illustrate a broad concept.

Phase 1

An exploratory panel consisting of 2 senior physiotherapists and 2 senior strength and conditioning coaches with significant experience in spinal training and rehabilitation in the EIS was formed to carry out an extended review of the literature (Table 1) to: i) Identify modifiable spinal abilities defining optimal function during skilled athletic performance; ii) clarify the impact of spinal pain/pathology on specific physical abilities; and iii) define categories of exercise objectives and physical outcomes. The literature search employed sensitive topic-based strategies designed for each database. Search dates were from database inception to 31st July 2013 to inform phase 1. The search has been recently updated to 31st July 2015 to reflect contemporary literature.

Databases

- CINAHL, EMBASE, and MEDLINE Databases
- Selected Internet sites and Indexes: PubMed

Search strategy

The search strategy included search terms informed by the conceptual framework. Specifically:

1] Anatomical and neuromuscular interactions in functional spinal control – Core, Stability (spinal), Function (spinal), Neuromuscular (control) 2] Spinal abilities defining optimal function during skilled athletic performance – Mobility, Motor Control, Strength Endurance, Strength, Rate of force development, Power, Performance (Athletic / Sporting) 3] Impact of spinal pain/pathology – Low back injury, Low back pain, Pathology (spine), Lumbar spine, Sport 4] Exercise specificity and physical adaptation – Training, Injury prevention, Rehabilitation, Exercise, Outcome measures, Physical/physiological adaptation. Studies not written in English were excluded from the analysis, but there were no restrictions on study design. 1614 studies were retrieved from the initial searches. Findings from studies were analysed in the context of any methodological limitations. Key themes and sub themes (e.g. exercise objective grouping, sub-classification requirements) were identified to inform the definition of physical abilities, exercise categories and physical outcomes.

Phase 2

An expert project group was convened to review/revise the initial panel findings. The group consisted of 5 physiotherapists and 5 strength and conditioning coaches holding national leadership positions within the EIS (Table 1), and regularly engaged in spinal training and rehabilitation. Independently they identified areas for discussion and review. Collectively they agreed modifications to the definition of physical abilities, exercise categories and physical outcomes, and a draft classification was formulated, informed by the study's conceptual framework. An example of an area discussed and modified was the requirement for work capacity and strength to be separated as two distinct physical performance parameters.

Phase 3

The draft classification was presented to all EIS physiotherapists (n=49) at a consensus forum, and sent to key experts in the field for international expert review. Data were analysed to inform emerging themes and sub-themes that were subsequently integrated into a revised classification. Examples of themes included understanding and managing practitioner bias, clarity of presentation, and agreed terminology/use of language.

Phase 4

The classification was presented to members of the EIS technical lead physiotherapy and strength and conditioning teams (n=17) for discussion. Discussion focused around the strengths of the framework and its potential application in elite sport.

Definition of consensus

Consensus was defined as unanimous agreement and this was achieved at each phase. The classification was accepted by unanimous agreement with minor amendments. The results section presents the definitive classification.

Figure 1: Flow diagram of consensus process.

Figure 2: Conceptual framework underpinning the study methods.

Table 1: Exploratory panel and expert project group participant characteristics

RESULTS

Objective 1:

Identification of modifiable spinal abilities which underpin optimal function during skilled athletic performance

Spinal abilities can be defined in four distinct categories: mobility, motor control, work capacity and strength[13-15 16]. It was important to consider the extent to which each category contributes to spinal neuromuscular control[5], the impact of pain/pathology, and how exercise interventions are utilised to influence targeted physical outcomes. Modifiable spinal abilities which underpin optimal function during skilled athletic performance are summarised in Figure 3 and defined in Appendix 1 (for online publication).

Mobility

Mobility is defined as freedom of movement at spinal segments and provides the basis for the development of motor control[17] and optimal spinal function[18]. Furthermore, the relationship between axial mobility and athletic performance has been established[19,20].

Deficits in spinal movement have been identified in athletes with a history of low back pain (LBP)[21-23], where changes in mobility are a product of the interaction between soft tissue and articular dysfunction. It is plausible that abnormal movement patterns or repetitive directional loading results in consistent absence of mechanical tension, associated with connective tissue remodelling and eventual loss of muscle fibre length[24,25]. Loss of mobility could also represent an adaptive or maladaptive mechanism by which the body attempts to achieve active stability and maintain a level function in the presence of pain, physical stress or failed motor control[26].

A myriad of therapeutic interventions are employed to influence neurophysical mechanisms associated with loss of mobility (hypomobility) such as focal articular/tissue restriction, pain and altered muscular tone[27]. Exercise is frequently utilised to influence spinal motion and mobility exercises can also be performed in combination with limb movement to augment tissue elongation throughout a continuous myofascial line[28]. Reliable assessment of spinal motion has been established[29-32]; and effective restoration of spinal range of motion following flexibility training has been demonstrated in the LBP population[33,34]. It should be noted that support for inclusion of this component within the classification is primarily based on clinical concepts.

Motor control

Maintenance of spinal integrity during skilled movement tasks is not only dependent on muscular capacity, but the ability to process sensory input, interpret the status of stability and motion, and establish strategies to overcome predictable and unexpected movement challenges[35]. The spinal stability required during athletic performance is task specific, governed by the nature of the intended movement, the magnitude of imposed load and the perception of risk associated with the activity[36]. The central nervous system therefore determines the requirements for stability and co-ordinates contraction of deep and superficial core muscles using both feed-forward and feedback control mechanisms[7,37]. In the presence of pain, the relationship between task demand for stability and muscular recruitment becomes incoherent, resulting in delayed trunk muscle reflex responses and excessive outer core muscular activation[38-40]. Classification systems have been developed to establish the nature of adaptive motor responses in the presence of pain, and identify maladaptive motor control impairments as a causative factor in spinal pain disorders[41,42].

Motor adaptation to pain has been demonstrated in athletes with LBP[43] and groin pain[44]; following recovery from a recent episode of LBP[45]; and is observable in recurrent LBP patients during periods of remission[46]. Furthermore, reflex response latencies can pre-exist within a healthy athletic population, significantly increasing the risk of sustaining a LSI[47]. There is evidence to suggest that motor adaptation to pain can be influenced through exercise-based intervention. Segmental stabilisation exercises first described by Richardson and Jull (1995)[48] focus on retraining coordinated co-contraction of the deep trunk muscles through simultaneous isometric co-contraction of transversus abdominis (TrA) and multifidus in a static neutral spine position. Exercise has been shown to be effective in restoring delayed/reduced activation of TrA[49] and multifidus[50], with positive effects persisting after cessation of training[51]. Despite its scientific foundation and widespread anecdotal support, impaired feed-forward activation of local stabilisation muscles in LBP patients has been challenged[52]. Furthermore, evidence has also questioned the ability to influence anticipatory muscle patterning following the performance of segmental stabilisation exercises[53] aligned with the preferential impact on pain and dysfunction in comparison to any other form of active exercise[54].

The ability to dissociate spinal and appendicular movement provides a static platform for force absorption/transference and is a product of mobility/neuromuscular control of the limbs, alongside the maintenance of a static neutral lumbar position. During sporting activities imparting high loads through the spine, it is important that forces are evenly distributed to minimise loading of vulnerable tissues in the spine[55, 56]. Inability to control a neutral position increases the potential for tissue damage, especially during repetitive loading activities. Clinical tests have been shown to reliably identify the performance of dissociation tasks under both low and high load conditions[57]; with movement control deficits identified in patients with LBP[58]. It is hypothesised that failed load transfer during low load conditions is primarily due to inadequate motor skill competence or altered mechanical behaviour associated with pain or the threat of pain or injury[59]. Failure under higher loads may be attributed to other factors (e.g. insufficient muscular capacity), requiring detailed assessment to establish the nature of the movement control loss.

During dynamic spinal movement, coordinated neuromuscular control of intersegmental articulation is provided by precise coordination of surrounding musculature[60]. Proximal to distal segmental sequencing is critical for the performance of skills which demand that maximum speed is produced at the end of the distal segment in the kinetic chain, such as kicking or throwing[19]. Failed load transfer during segmental motion results in aberrant motor patterns, which could hypothetically result in tissue damage through uneven load distribution and focal tissue stress [42,61]. Conversely, changes in motor control in some LBP subgroups have been associated with a compromised ability to coordinate spinal motion (due to excessive aberrant muscular co-contraction) resulting in an inability to perform controlled segmental movements[62]. Sequential segmental control exercises (for instance dynamic pelvic-tilting) are intended to establish or retrain appropriate muscular recruitment, co-ordinated dynamic motor control and proprioceptive awareness[63].

Facilitation of skilled motor learning during rehabilitation requires autonomous engagement in the learning process[64]. Once the subject is motivated to learn a new motor skill, it is important to clearly detail the new task to be learned (e.g. through instruction, demonstration)[65]. In addition, the process must provide neuromuscular challenge through progressive difficulty[66] and variability[67], underpinned by regular deliberate practice[68] with appropriate knowledge of results and performance related to the task[69].

Work Capacity (WC)

Work capacity (WC) is synonymous with local muscular endurance[70]. This can be defined as the ability to produce or tolerate variable intensities and durations of work and contributes to the ability of an athlete to perform efficiently in a given sport[70,71]. WC is a training outcome and not a performance outcome test. The accumulation of training over many weeks and months results in chronic local adaptation to muscle, tendon and metabolic biogenesis[72-79]. This chronic local adaptation increases the ability of the system to produce more work during repeated efforts, allows the local musculature to tolerate (or demonstrate resilience to) a larger training volume of work[71] and supports the performance of work closer to the intensity and duration required for sporting performance.

By comparison, strength endurance has been described as a performance outcome test completed in isolation whereby the goal is to achieve a specific amount of work at a given intensity such as maximum number of repetitions at 50% of one repetition maximum or at a specific submaximal load[80-82] with less emphasis placed on the physiological adaptation required for WC development. The American College of Sports Medicine (ACSM) have also defined strength endurance, as 'high intensity' endurance. As a result, strength endurance can be used as a proxy measure of work capacity or as a training variable within work capacity[70].

Failure to meet mechanical loading demands through insufficient neuromuscular capacity may result in loss of optimal motor control and biomechanical inefficiency[83]. Trunk WC is underpinned by the ability to transfer, absorb or dissipate, repeated or sustained submaximal forces through appropriate strength endurance; providing a platform for the development and performance of specific strength qualities.

Reduction in trunk muscle endurance and changes in endurance ratios have been identified in patients with a history of LBP[84-86]; and insufficient abdominal muscular endurance has been identified as a risk factor in injury recurrence[87]. Furthermore, structural degeneration of lumbar musculature in LBP patients has been characterised by fatty infiltration, muscular atrophy and fiber-type modification[88,89]. Static stabilisation ('pillar') exercises are frequently prescribed in an attempt to produce sufficient muscular activation to develop spinal endurance qualities during rehabilitation[12]. Targeted exercise has been shown to improve muscular strength[90], endurance[91] and cross sectional area[92].

Strength

Muscular strength can be defined as the ability to produce force, with maximal strength being the largest force the musculature can produce[93]. Rate of force development (RFD) has been defined as the rate of rise of contractile force at the beginning of a muscle action and is time dependent[94]. RFD from trunk musculature can either augment global external power production (dynamic RFD) or protect the spine by 'stiffening' against yielding forces (static RFD). The production of force/torque and stiffness depends on morphological and neurological factors from the neuromuscular system. Morphological factors include cross-sectional area, muscle pennation angle, fascial length and fibre type[95]. Neurological factors include motor unit recruitment, firing frequency, motor unit synchronisation and inter-muscular coordination[96].

Dynamic RFD / power - there is a growing body of evidence showing that athletes who produce the greatest external powers are the most successful in their events[97,98]. Peak RFD has a strong relationship with peak power and has been used as a proxy measure of peak power[93]. Watkins et al. (1996)[99] suggest the trunk musculature assists in stabilising and controlling the load response for maximal power during movements such as the golf swing. During a single movement, maximal power is the greatest instantaneous power with the aim of producing maximal velocity of movements such as striking, kicking, jumping or throwing[100]. All of these tasks require segmental sequential coordination to augment external global power output.

Static RFD / stiffness - could be defined as the ability of the trunk to resist deformation from yielding forces to maintain spinal posture[101,102]. Muscular trunk stiffness requires contractile forces equal to the rate, direction and magnitude exerted against the trunk to minimise the transmission of force to the spine itself. Similar morphological and neurological qualities are required for appropriate stiffness capabilities as for power production[96,103,104]. The demand of the task can require the trunk to brace against a rapid RFD under relatively low loads, biasing challenge towards the neurological system[105]. By contrast, a high-imparted force also challenges the neurological system but requires the morphological qualities of the trunk musculature to produce stiffness large enough to protect the stability of the spine[95,106].

The association between trunk strength and the presence of LBP remains unclear, with evidence to support[107-110] and contest[111,112] the relationship. Despite the suggestion that trunk endurance provides greater prophylactic value[113], strength and power is an essential physical requirement for performance in many sports and represents the final stages of exercise progression for athletes during rehabilitation from LSI[15]. In addition, failure to redevelop sufficient trunk strength during the rehabilitation process may compromise the ability to maintain spinal integrity on return to sporting activity and increase the risk of injury reoccurrence.

Figure 3: Classification of modifiable spinal abilities positioned within the context of physical ability.

Objective 2: Classification of spinal exercises according to objective of the exercise and intended physical outcomes

The classification of exercises is informed through empirical literature (e.g. motor control, work capacity and strength) alongside the application of research within clinical practice (e.g. mobility development). Exercises were classified according to the objective of the exercise and the intended physical outcome. In addition, exercises were also sub-classified by functionality, as either non-functional (NF) or functional (F); and by spinal displacement as either static (maintenance of a neutral spinal posture with no appreciable segmental displacement) or dynamic (exercises involving appreciable dynamic segmental movement).

Sub-classification 1: Functionality

Functional exercises have been described as a continuum of exercises to enable athletes to effectively manipulate their bodyweight in all planes of movement to achieve optimal athletic performance[17]. Functional exercises are performed in weight bearing (standing, single leg standing, squatting, lunging) or sport specific positions (multiple planes of motion involving multiple joints). By contrast, non-functional exercises are typically performed in partial weight bearing positions (sitting, kneeling, prone kneeling, lying) across a single plane of motion with movement isolated to fewer joints[114]. An advantage of non-functional spinal exercises is the ability to influence mechanical loading within specifically targeted muscle groups through use of gravitational force, lever length (by manipulating body position), and superimposed load[115]. Both non-functional and functional spinal exercise prescription can be utilised to develop effective interaction (dynamic correspondence[116]) between physical abilities into sport specific performance.

Sub-classification 2: Spinal displacement

During athletic activity, spinal function provides a static platform for force absorption/transference or a dynamic contribution to whole body motion. The requirement for these abilities is dependent on the movement demands of the sport which frequently requires both components. During activities exposed to high loading characteristics, the central nervous system employs stiffening strategies by co-contraction of antagonist trunk muscles with little or no appreciable segmental displacement. In contrast, during tasks requiring appreciable dynamic segmental movement, the central nervous system controls segmental motion through precision of timing and pattern of muscle activity[14]. The ability to dissociate spinal and appendicular motion, and perform sequential segmental spinal movement represents two discrete skill based movement competencies.

Spinal Exercise Classification (SEC)

The definitive SEC is summarised in Figure 4. Definitions of each exercise objective and examples of exercises related to each intended physical outcome are displayed in Table 2 and Figures 5-11. Exercises can be further delineated by plane of motion and/or globally targeted muscular contraction[115] (e.g. sagittal plane movement, anterior chain muscular activation).

Figure 4. Spinal Exercise Classification (SEC) with exercise objectives positioned within context of intended physical outcome

Table 2. Exercise objective definitions positioned within context of intended physical outcome

Figure 5. Mobility development - example exercises (a – flexion, b – extension, c – lateral flexion, d – rotation)

Figure 6. Motor Control - example exercises, a) segmental stabilisation (non-functional) b) spinal dissociation (non-functional), c) spinal dissociation (functional), d) segmental movement control (non-functional), e) whole body co-ordination (functional)

Figure 7. Work Capacity - example exercises, a) pillar conditioning (non-functional), b) pillar conditioning (functional)

Figure 8. Work Capacity - example exercises, a) segmental conditioning (non-functional), b) segmental conditioning (functional)

Figure 9. Strength - example exercises, pillar strength development (non-functional)

Figure 10. Strength - example exercises, static rate of force / stiffness development (functional). Note exercise selection biased towards morphological adaptation (a) and neurological adaptation (b)

Figure 11. Strength - example exercises, dynamic rate of force / power development (functional)

DISCUSSION

Historically, there has been confusion regarding CS, how it is trained and its application to functional performance[9]. In addition, the most effective exercises for the treatment of LBP remain largely unknown and research evidence is unable to direct specific exercise prescription for a given pathological subgroup. During recent years, research has highlighted the complex interaction between anatomical, neurophysiological and psychosocial factors influencing spinal control. Failure to synthesise contemporary evidence can lead to reductionist opinion and uni-dimensional paradigms of exercise prescription; when in reality, the spine functions across a vast spectrum of movement demands, demonstrating complex interactions between many different modifiable physical abilities.

A qualitative consensus methodology was employed to systematically define the classification system to ensure acceptability to elite sport practitioners. The 4 phases worked well to ensure challenge to identified themes and sub themes with conclusions drawn from those experienced in sport at the elite level. The definitive SEC consolidates approaches to spinal exercise to develop a practical, conceptual representation of rehabilitation options applicable within a diverse spectrum of musculoskeletal practice. Furthermore, the classification supports multidisciplinary team integration within the rehabilitation process; demonstrating validity for use by strength and conditioning professionals as the athlete transitions towards performance focussed training following injury.

The intention of the SEC is to encourage detailed clinical reasoning, where practitioners identify specific physical dysfunction(s) and consider exercise prescription within the context of a clinical diagnosis and/or prevailing circumstances (e.g. sport specific performance targets). Once determined, targeted exercise objectives define the nature of the exercise prescription required to deliver an intended physical outcome. In order for practitioners to effectively use the SEC, spinal abilities need to be identified using outcome measures with established measurement properties. Moreover, athletes are frequently able to compensate for sub-optimal abilities in various aspects of physical performance. Where the process of athlete evaluation identifies multidimensional physical dysfunction, restoration of mobility and fundamental motor control must precede the development of work capacity and strength.

It is intended that the SEC provides a platform for further research. Future studies are required to establish patterns of physical dysfunction within specific pathological subgroups; evaluate the efficacy of exercise prescription in the development of specific physical performance abilities; and evaluate the effect of targeted exercise within sporting populations with pathology. The ability to exhibit a wide breadth of physical abilities enhances performance and supports the capacity to adapt to the variable nature of stress during sporting activity; contributing to the foundation of injury prevention[117].

The strengths of this study are its attempt to define a common language, integration of a breadth of literature and the intent to comprehensively evolve and incorporate (rather than replace or discredit) existing theoretical frameworks extrapolated from a rapidly expanding knowledge base. The key limitation to this study is the predominantly national focus to the consensus process, although international experts were included at key stages.

CONCLUSION

Maintenance of spinal integrity during skilled athletic performance requires precise neuromuscular control in order to balance task demands for stability and motion. Economy of motion is a function of discrete, interdependent physical abilities. When investigating intrinsic contribution to spinal injury, reductionist approaches may fail to accurately identify factors associated with causality and predisposition. Furthermore, comprehensive restoration of physical abilities during rehabilitation is fundamental in the attainment of athletic performance and mitigation of injury risk on return to sporting activity. Exercise specificity forms the basis of targeted adaptation, where intended physical outcome must dictate the nature of exercise prescription. The SEC contextualises spinal function and provides a basis for clinical reasoning and targeted exercise selection in the prevention and management of spinal injuries in sport.

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REFERENCES

1. Tall RL, DeVault W. Spinal injury in sport: epidemiologic considerations. *Clin Sports Med*. 1993;12(3):441-448.

2. Bono CM. Low-back pain in athletes. *The Journal of bone and joint surgery American volume*. 2004;86-A(2):382-396.

3. Trainor TJ, Trainor MA. Etiology of low back pain in athletes. *Current sports medicine reports*. 2004;3(1):41-46.

4. d'Hemecourt PA, Gerbino PG, Micheli LJ. Back injuries in the young athlete. *Clin Sports Med*. 2000;19(4):663-679.

5. Ben Kibler W, Press J, Sciascia A. The role of core stability in athletic function. *Sports medicine*. 2006;36(3):189-198.

6. Cook G. Baseline Sports-Fitness Testing. In: *High-Performance Sports Conditioning*. 2001:19-47.

7. Akuthota V, Ferreiro A, Moore T, Fredericson M. Core stability exercise principles. *Current sports medicine reports*. 2008;7(1):39-44.

8. Hodges P. Transversus abdominis: a different view of the elephant. *British journal of sports medicine*. 2008;42(12):941-944.

9. Faries M, Greenwood M. Core Training: stabilizing the confusion. *Strength and Conditioning Journal*. 2007;29(2):10-25.

10. Hodges PW. Core stability exercise in chronic low back pain. *The Orthopedic clinics of*

North America. 2003;34(2):245-254.

11. Vleeming A, Vert Mooney MD, Stoeckart R. *Movement, Stability and Lumbopelvic Pain*. Churchill Livingstone; 2007:489-561.

12. Kavcic N, Grenier S, McGill SM. Determining the stabilizing role of individual torso muscles during rehabilitation exercises. *Spine*. 2004;29(11):1254-1265.

13. Cook G. *Athletic Body in Balance*. Stackpole Books; 2003:26-30.

14. Hodges P, Cholewicki J. Functional control of the spine. In: *Movement, Stability and Lumbopelvic Pain*. Churchill Livingstone; 2007:489-512.

15. McGill S. *Ultimate Back Fitness and Performance*. 2006:277-285.

16. Hodges PW, Gurfinkel VS, Brumagne S, Smith TC, Cordo PC. Coexistence of stability and mobility in postural control: evidence from postural compensation for respiration. *Exp Brain Res*. 2002;144(3):293-302.

17. Boyle M. *Advances in Functional Training*. On Target Publications; 2012:31-34.

18. Pepin JK, Preston D. Effects of Hold-Relax and Active Range of Motion on Thoracic Spine Mobility. *J Int Acad Phys Ther Res*. 2012.

19. Marshall RN, Elliott BC. Long-axis rotation: the missing link in proximal-to-distal segmental sequencing. *J Sports Sci*. 2000;18(4):247-254.

20. Young JL, Herring SA, Press JM, Casazza BA. The influence of the spine on the shoulder in the throwing athlete. *J Back Musculoskelet Rehabil*. 1996;7(1):5-17.

21. Vad VB, Bhat AL, Basrai D, Gebeh A, Aspergren DD, Andrews JR. Low back pain in

professional golfers: the role of associated hip and low back range-of-motion deficits. *Am J Sports Med*. 2004;32(2):494-497.

22. Campbell A, O'Sullivan P, Straker L, Elliott B, Reid M. Back pain in tennis players: a link with lumbar serve kinematics and range of motion. *Med Sci Sports Exerc*. 2014;46(2):351-357.

23. Lindsay D, Horton J. Comparison of spine motion in elite golfers with and without low back pain. *J Sports Sci*. 2002;20(8):599-605.

24. Langevin HM, Sherman KJ. Pathophysiological model for chronic low back pain integrating connective tissue and nervous system mechanisms. *Medical hypotheses*. 2007;68(1):74-80.

25. Sahrmann S. *Diagnosis and Treatment of Movement Impairment Syndromes*. Elsevier Health Sciences; 2002:12-13.

26. Cook G. *Movement*. Lotus Pub.; 2011:26-28.

27. Simmonds N, Miller P, Gemmell H. A theoretical framework for the role of fascia in manual therapy. *Journal of bodywork and movement therapies*. 2012;16(1):83-93.

28. Schleip R, Müller DG. Training principles for fascial connective tissues: scientific foundation and suggested practical applications. *J Bodyw Mov Ther*. 2013;17(1):103-115.

29. Anderson VB. The intra-rater reliability of measured thoracic spine mobility in chronic rotator cuff pathology. *J Musculoskelet Neuronal Interact*. 2011;11(4):314-319.

30. Heneghan NR, Hall A, Hollands M, Balanos GM. Stability and intra-tester reliability of an in vivo measurement of thoracic axial rotation using an innovative methodology. *Man Ther*.

2009;14(4):452-455.

31. Johnson KD, Kim K-M, Yu B-K, Saliba SA, Grindstaff TL. Reliability of thoracic spine rotation range-of-motion measurements in healthy adults. *J Athl Train*. 2012;47(1):52-60.

32. Kellis E, Adamou G, Tzilios G, Emmanouilidou M. Reliability of spinal range of motion in healthy boys using a skin-surface device. *J Manipulative Physiol Ther*. 2008;31(8):570-576.

33. Battaglia G, Bellafiore M, Caramazza G, Paoli A, Bianco A, Palma A. Changes in spinal range of motion after a flexibility training program in elderly women. *Clin Interv Aging*. 2014;9:653-660.

34. Kuukkanen T, Mälkiä E. Effects of a three-month therapeutic exercise programme on flexibility in subjects with low back pain. *Physiother Res Int*. 2000;5(1):46-61.

35. Hodges PW, Moseley GL. Pain and motor control of the lumbopelvic region: effect and possible mechanisms. *Journal of electromyography and kinesiology*. 2003;13(4):361-370.

36. van Dieën JH, de Looze MP. Directionality of anticipatory activation of trunk muscles in a lifting task depends on load knowledge. *Exp Brain Res*. 1999;128(3):397-404.

37. Diedrichsen J, Shadmehr R, Ivry RB. The coordination of movement: optimal feedback control and beyond. *Trends in cognitive sciences*. 2010;14(1):31-39.

38. Silfies SP, Squillante D, Maurer P, Westcott S, Karduna AR. Trunk muscle recruitment patterns in specific chronic low back pain populations. *Clin Biomech*. 2005;20(5):465-473.

39. van Dieën JH, Selen LPJ, Cholewicki J. Trunk muscle activation in low-back pain patients, an analysis of the literature. *J Electromyogr Kinesiol*. 2003;13(4):333-351.

40. van Dieën JH, Cholewicki J, Radebold A. Trunk muscle recruitment patterns in patients with low back pain enhance the stability of the lumbar spine. *Spine*. 2003;28(8):834-841.

41. O'Sullivan P. Diagnosis and classification of chronic low back pain disorders: maladaptive movement and motor control impairments as underlying mechanism. *Man Ther*. 2005;10(4):242-255.

42. Van Dillen LR, Sahrmann SA, Norton BJ, Caldwell CA, Fleming DA, McDonnell MK, Woolsey NB. Reliability of physical examination items used for classification of patients with low back pain. *Phys Ther*. 1998;78(9):979-988.

43. Hides JA, Boughen CL, Stanton WR, Strudwick MW, Wilson SJ. A magnetic resonance imaging investigation of the transversus abdominis muscle during drawing-in of the abdominal wall in elite Australian Football League players with and without low back pain. *J Orthop Sports Phys Ther*. 2010;40(1):4-10.

44. Cowan SM, Schache AG, Brukner P, Bennell KL, Hodges PW, Coburn P, Crossley KM. Delayed onset of transversus abdominus in long-standing groin pain. *Med Sci Sports Exerc*. 2004;36(12):2040-2045.

45. Cholewicki J, Greene HS, Polzhofer GK, Galloway MT, Shah RA, Radebold A. Neuromuscular function in athletes following recovery from a recent acute low back injury. *J Orthop Sports Phys Ther*. 2002;32(11):568-575.

46. D'hooge R, Hodges P, Tsao H, Hall L, Macdonald D, Danneels L. Altered trunk muscle coordination during rapid trunk flexion in people in remission of recurrent low back pain. *J Electromyogr Kinesiol*. 2013;23(1):173-181.

47. Cholewicki J, Silfies SP, Shah RA, Greene HS, Reeves NP, Alvi K, Goldberg B. Delayed trunk

muscle reflex responses increase the risk of low back injuries. *Spine*. 2005;30(23):2614-2620.

48. Richardson CA, Jull GA. Muscle control-pain control. What exercises would you prescribe? *Man Ther*. 1995;1(1):2-10.

49. Tsao H, Hodges PW. Immediate changes in feedforward postural adjustments following voluntary motor training. *Exp Brain Res*. 2007;181(4):537-546.

50. Tsao H, Druitt TR, Schollum TM, Hodges PW. Motor training of the lumbar paraspinal muscles induces immediate changes in motor coordination in patients with recurrent low back pain. *J Pain*. 2010;11(11):1120-1128.

51. Tsao H, Hodges PW. Persistence of improvements in postural strategies following motor control training in people with recurrent low back pain. *J Electromyogr Kinesiol*. 2008;18(4):559-567.

52. Gubler D, Mannion AF, Schenk P, Gorelick M, Helbling D, Gerber H, Toma V, Sprott H. Ultrasound tissue Doppler imaging reveals no delay in abdominal muscle feed-forward activity during rapid arm movements in patients with chronic low back pain. *Spine*. 2010;35(16):1506-1513.

53. Vasseljen O, Unsgaard-Tøndel M, Westad C, Mork PJ. Effect of core stability exercises on feed-forward activation of deep abdominal muscles in chronic low back pain: a randomized controlled trial. *Spine*. 2012;37(13):1101-1108.

54. Smith BE, Littlewood C, May S. An update of stabilisation exercises for low back pain: a systematic review with meta-analysis. *BMC Musculoskelet Disord*. 2014;15(1):416.

55. Adams MA, Dolan P. How to use the spine, pelvis, and legs effectively in lifting. In: *Movement, Stability and Lumbopelvic Pain*. Churchill Livingstone; 2007:167-183.

56. Cholewicki J, McGill SM. Lumbar posterior ligament involvement during extremely heavy lifts estimated from fluoroscopic measurements. *J Biomech*. 1992;25(1):17-28.

57. Monnier A, Heuer J, Norman K, Äng BO. Inter- and intra-observer reliability of clinical movement-control tests for marines. *BMC Musculoskelet Disord*. 2012;13(1):263.

58. Luomajoki H, Kool J, de Bruin ED, Airaksinen O. Movement control tests of the low back; evaluation of the difference between patients with low back pain and healthy controls. *BMC Musculoskelet Disord*. 2008;9:170.

59. Hodges PW. Pain and motor control: From the laboratory to rehabilitation. *Journal of electromyography and kinesiology*. 2011;21(2):220-228.

60. Panjabi MM. Clinical spinal instability and low back pain. *Journal of electromyography and kinesiology.* 2003;13(4):371-379.

61. Harris-Hayes M, Van Dillen LR, Sahrmann SA. Classification, treatment and outcomes of a patient with lumbar extension syndrome. *Physiother Theory Pract*. 2005;21(3):181-196.

62. Elqueta-Cancino E, Schabrun S, Danneels L, Hodges P. A clinical test of lumbopelvic control: Development and reliability of a clinical test of dissociation of lumbopelvic and thoracolumbar motion. *Man Ther*. 2014;19(5):418-24.

63. Brumagne S, Lysens R, Spaepen A. Lumbosacral position sense during pelvic tilting in men and women without low back pain: test development and reliability assessment. *J Orthop Sports Phys Ther*. 1999;29(6):345-351.

64. Higgins S. Motor skill acquisition. *Phys Ther*. 1991;71(2):123-139.

65. Schmidt RA. *Motor Learning and Performance*. Human Kinetics; 2008:379-384.

66. Guadagnoli MA, Lee TD. Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of motor behavior*. 2004;36(2):212-224.

67. Ranganathan R, Newell KM. Changing up the routine: intervention-induced variability in motor learning. *Exercise and sport sciences reviews*. 2013;41(1):64-70.

68. Ericsson K, Krampe R, Tesch-Römer C. The role of deliberate practice in the acquisition of expert performance. *Psychological review*. 1993;100(3):363-406.

69. Salmoni AW, Schmidt RA, Walter CB. Knowledge of results and motor learning: a review and critical reappraisal. *Psychol Bull*. 1984;95(3):355-386.

70. Ratamess NA, Alvar A, Evetoch TK, Housh TJ, Kibler WB, Kraemer WJ, Triplett NT. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Med Sci Sports Exerc*. 2009;41(3):687-708.

71. Siff MC. *Supertraining*. Supertraining Institute; 2003:32-33.

72. Van Cutsem M, Duchateau J, Hainaut K. Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *The Journal of Physiology*. 1998;513(1):295-305.

73. Connor MK, Bezborodova O, Escobar CP, Hood DA. Effect of contractile activity on protein turnover in skeletal muscle mitochondrial subfractions. *J Appl Physiol*. 2000;88(5):1601-1606.

74. Frontera WR, Hughes VA, Fielding RA, Fiatarone MA, Evans WJ, Roubenoff R. Aging of skeletal muscle: a 12-yr longitudinal study. *J Appl Physiol*. 2000;88(4):1321-1326.

75. Langberg H, Skovgaard D, Asp S, Kjaer M. Time pattern of exercise-induced changes in type I collagen turnover after prolonged endurance exercise in humans. *Calcif Tissue Int*. 2000;67(1):41-44.

76. Miller BF, Olesen JL, Hansen M, Dossing S, Crameri RM, Welling RJ, Langberg H, Flyvberg A, Kjaer M, Babraj JA, Smith K, Rennie MJ. Coordinated collagen and muscle protein synthesis in human patella tendon and quadriceps muscle after exercise. *The Journal of Physiology*. 2005;567(Pt 3):1021-1033.

77. Kongsgaard M, Reitelseder S, Pedersen TG, Holm L, Aagaard P, Kjaer M, Magnusson SP. Region specific patellar tendon hypertrophy in humans following resistance training. *Acta Physiol*. 2007;191(2):111-121.

78. Burd NA, West DWD, Staples AW, Atherton PJ, Baker JM, Moore DR, Holwerda AM, Parise G, Rennie MJ, Baker SK, Phillips SM. Low-load high volume resistance exercise stimulates muscle protein synthesis more than high-load low volume resistance exercise in young men. *PLoS ONE*. 2010;5(8):e12033.

79. Gonzalez Castro LN, Monsen CB, Smith MA. The binding of learning to action in motor adaptation. *PLoS Comput Biol*. 2011;7(6):e1002052.

80. Liu Y, Lormes W, Wang L, Reissnecker S, Steinacker JM. Different skeletal muscle HSP70 responses to high-intensity strength training and low-intensity endurance training. *Eur J Appl Physiol*. 2004;91(2-3):330-335.

81. Naclerio FJ, Colado JC, Rhea MR, Bunker D, Triplett NT. The influence of strength and

power on muscle endurance test performance. *J Strength Cond Res*. 2009;23(5):1482-1488.

82. Jürimäe T, Perez-Turpin JA, Cortell-Tormo JM, Chinchilla-Mira IJ, Cejuela-Anta R, Maestu J, Purge P, Jürimäe J . Relationship between rowing ergometer performance and physiological responses to upper and lower body exercises in rowers. *J Sci Med Sport*. 2010;13(4):434-437.

83. Borghuis J, Hof AL, Lemmink KAPM. The importance of sensory-motor control in providing core stability: implications for measurement and training. *Sports medicine*. 2008;38(11):893-916.

84. Salminen JJ, Maki P, Oksanen A, Pentti J. Spinal mobility and trunk muscle strength in 15-year-old schoolchildren with and without low-back pain. *Spine*. 1992;17(4):405-411.

85. Bo Andersen L, Wedderkopp N, Leboeuf-Yde C. Association between back pain and physical fitness in adolescents. *Spine*. 2006;31(15):1740-1744.

86. McGill S, Grenier S, Bluhm M, Preuss R, Brown S, Russell C. Previous history of LBP with work loss is related to lingering deficits in biomechanical, physiological, personal, psychosocial and motor control characteristics. *Ergonomics*. 2003;46(7):731-746.

87. Jones MA, Stratton G, Reilly T, Unnithan VB. Biological risk indicators for recurrent non-specific low back pain in adolescents. 2005;39(3):137-140.

88. Danneels LA, Vanderstraeten GG, Cambier DC, Witvrouw EE, De Cuyper HJ. CT imaging of trunk muscles in chronic low back pain patients and healthy control subjects. *Eur Spine J*. 2000;9(4):266-272.

89. D'hooge R, Cagnie B, Crombez G, Vanderstraeten G, Dolphens M, Danneels L. Increased intramuscular fatty infiltration without differences in lumbar muscle cross-sectional area during remission of unilateral recurrent low back pain. *Man Ther*. 2012;17(6):584-588.

90. Keller A, Brox JI, Gunderson R, Holm I, Friis A, Reikerås O. Trunk muscle strength, cross-sectional area, and density in patients with chronic low back pain randomized to lumbar fusion or cognitive intervention and exercises. *Spine*. 2004;29(1):3-8.

91. Durall CJ, Udermann BE, Johansen DR, Gibson B, Reineke DM, Reuteman P. The effects of preseason trunk muscle training on low-back pain occurrence in women collegiate gymnasts. *J Strength Cond Res*. 2009;23(1):86-92.

92. Danneels LA, Vanderstraeten GG, Cambier DC, Witvrouw EE, Bourgois J, Dankaerts W, De Cuyper HJ. Effects of three different training modalities on the cross sectional area of the lumbar multifidus muscle in patients with chronic low back pain. 2001;35(3):186-191.

93. Stone MH, Sands WA, Carlock J, Callan S, Dickie D, Daigle K, Cotton J, Smith SL, Hartman M. The importance of isometric maximum strength and peak rate-of-force development in sprint cycling. *J Strength Cond Res*. 2004;18(4):878-884.

94. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol*. 2002;93(4):1318-1326.

95. Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power: Part 1--biological basis of maximal power production. *Sports Med*. 2011;41(1):17-38.

96. Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *J Strength Cond Res*.

2009;23(1):177-186.

97. Stone MH, Sanborn K, O'Bryant HS, Hartman M, Stone ME, Proulx C, Ward B, Hruby J. Maximum strength-power-performance relationships in collegiate throwers. *J Strength Cond Res*. 2003;17(4):739-745.

98. Nimphius S, McGuigan MR, Newton RU. Relationship between strength, power, speed, and change of direction performance of female softball players. *J Strength Cond Res*. 2010;24(4):885-895.

99. Watkins RG, Uppal GS, Perry J, Pink M, Dinsay JM. Dynamic electromyographic analysis of trunk musculature in professional golfers. *Am J Sports Med*. 1996;24(4):535-538.

100. Newton RU, Kraemer WJ. Developing Explosive Muscular Power: Implications for a Mixed Methods Training Strategy. J Strength Cond. 1994;16:20-31.

101. Graham RB, Brown SHM. A direct comparison of spine rotational stiffness and dynamic spine stability during repetitive lifting tasks. *J Biomech*. 2012;45(9):1593-1600.

102. Brown SHM, McGill SM. How the inherent stiffness of the in vivo human trunk varies with changing magnitudes of muscular activation. *Clin Biomech*. 2008;23(1):15-22.

103. Brughelli M, Cronin J. A review of research on the mechanical stiffness in running and jumping: methodology and implications. 2008;18(4):417-426.

104. Chelly SM, Denis C. Leg power and hopping stiffness: relationship with sprint running performance. *Med Sci Sports Exerc*. 2001;33(2):326-333.

105. Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power: part 2 - training considerations for improving maximal power production. *Sports Med*.

2011;41(2):125-146.

106. Brown SHM, McGill SM. Muscle force-stiffness characteristics influence joint stability: a spine example. *Clin Biomech*. 2005;20(9):917-922.

107. Bayramoğlu M, Akman MN, Kilinç S, Cetin N, Yavuz N, Ozker R. Isokinetic measurement of trunk muscle strength in women with chronic low-back pain. *Am J Phys Med Rehabil*. 2001;80(9):650-655.

108. McNeill T, Warwick D, Andersson G, Schultz A. Trunk strengths in attempted flexion, extension, and lateral bending in healthy subjects and patients with low-back disorders. *Spine*. 1980;5(6):529-538.

109. Davarian S, Maroufi N, Ebrahimi I, Farahmand F, Parnianpour M. Trunk muscles strength and endurance in chronic low back pain patients with and without clinical instability. *J Back Musculoskelet Rehabil*. 2012;25(2):123-129.

110. McGill SM, Grenier S, Kavcic N, Cholewicki J. Coordination of muscle activity to assure stability of the lumbar spine. *Journal of electromyography and kinesiology*. 2003;13(4):353-359.

111. Paalanne N, Korpelainen R, Taimela S, Remes J, Mutanen P, Karppinen J. Isometric trunk muscle strength and body sway in relation to low back pain in young adults. *Spine*. 2008;33(13):E435-E441.

112. Renkawitz T, Boluki D, Grifka J. The association of low back pain, neuromuscular imbalance, and trunk extension strength in athletes. *Spine J*. 2006;6(6):673-683.

113. McGill SM. Low back exercises: evidence for improving exercise regimens. *Phys Ther*.

1998;78(7):754-765.

114. Gambetta V. *Athletic Development*. New World Library; 2007:3-4.

115. Floyd RT, Thompson C. Basic Biomechanical Factors and Concepts. In: *Manual of Structural Kinesiology*. McGraw-Hill; 2009:69-86.

116. Siff MC. Dynamic Correspondence as a Means of Strength Training. In: *Supertraining*. Supertraining Institute; 2003:240-252.

117. Glasgow P, Bleakley CM, Phillips N. Being able to adapt to variable stimuli: the key driver in injury and illness prevention? *British journal of sports medicine*. 2013;47(2):64-65.